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Design and Fabrication of a Micro-Ion Engine

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A micro-ion engine is being developed with micromachined grids and cathodes. This article describes the configuration of the discharge chamber and design and fabrication of the grids and field emission array (FEA) cathodes. The dicharge chamber is conventionally machined from stainless steel in the prototype configuration presented in this study. Discharge chamber diameters of 1, 2, and 3 cm were fabricated and will be studied experimentally, with results to be compared to a numerical model in order to optimize the design. A novel Chemical Etched Miniature Systems (ChEMS™) technology developed by Vacco Industries was used to machine molybdenum grids with screen hole aperture diameters of 330 microns and accelerator hole diameters of 200 microns. Field emitter array studies involve the test and evaluation of various cathode materials, such as molybdenum, silicon, and various thin film coatings, such as hafnium carbide or zirconium carbide. Theoretical and experimental performance evaluations of field emission array cathodes in simulated thruster environments are also described to motivate the cathode configuration under development. In addition, micromachined ion repeller grids (Cathode Lens and Ion Repellers – CLAIR) are being investigated, which are intended to keep plasma ions from reaching the field emitter tips, thus increasing cathode lifetime.

I. INTRODUCTION

The advent of the microspacecraft concept, representing a class of spacecraft of a few kilogram or less total wet mass[1,2] has created a need for new, miniaturized propulsion components. Among these, thruster components will be required to deliver very small thrust values (milli-Newtons and below) and low impulse bits (micro-Newton-seconds), and may feature engine sizes and masses orders of magnitude smaller than are available with current thruster hardware. Primary propulsion applications may also require the use of high-specific-impulse thrusters in order to keep propellant mass and, thus, total spacecraft weight low.

In addition to microspacecraft, the National Aeronautics and Space Administration (NASA) is currently considering new classes of missions, such as interferometry missions and missions involving large inflatable spacecraft[3] that may require micro-thrusters. In the case of interferometry missions there exists a need to precisely control the positioning of a constellation of craft[3]. In fact, high-specific-impulse and low-thrust devices are being considered mission critical for this type of mission[3]. Large inflatable craft[3], on the other hand, may experience solar-pressure induced disturbance torques acting on the large inflated spacecraft surfaces. A quasi-continous, low-level thrust will be required to offset these torques. High-specific impulse, miniaturized thrusters that could be integrated with the inflatable structure, thus taking advantage of potentially large moment arms provided by this structure, may be highly beneficial to this class of missions.

Several high-specific-impulse, low-thrust propulsion options already exist, namely Field Emission Electric Propulsion (FEEP), colloid thrusters, and pulsed plasma thrusters (PPTs)[4]. Both FEEP and PPT systems have reached high degrees of maturity and have either already been used in space applications, or may do so in the near future. At present, however, several concerns related to the use of these thrusters still persist. All three thruster types may pose contamination concerns due to the types of propellants used. Typically, FEEP systems use cesium or indium propellants, colloid thrusters use glycerol propellants doped with sodium iodine, and PPT thrusters employ Teflon propellants. These propellants may condense on surfaces of sensitive spacecraft components (lenses of optical instruments, inflatable antenna surfaces, solar arrays, etc.) and subsequently interfere with the proper function of these components. While fears of spacecraft contamination due to backflow from thrusters onto the spacecraft to which these thrusters are mounted have been alleviated somewhat as a result of dedicated contamination studies [4,5,6,7,8], such concerns at present do persist in constellation flying applications. In these applications, thrusters on one spacecraft may fire directly onto a neighboring craft, substantially increasing contamination risk depending on the distance between the craft. In the aforementioned application of inflatable spacecraft, large inflatable antennas may be envisioned. Any conductive

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(2)Group Supervisor, Advanced Propulsion Technology Group propellant able to condense on such antenna surfaces, like cesium or indium, may represent a risk of interfering with antenna operation. In addition, at present, available hardware for the three thruster types given above is still fairly large and power consuming, although several efforts are underway to further miniaturize these technologies[4,9,10,11].

Thus, there appears to be a niche application for a high-specific-impulse, low-thrust micro-thruster using more benign propellants. A miniature xenon ion engine may fit such a need. At present, no such engine exists. Currently available ion engine thruster hardware is far too heavy and power consuming to be considered for applications as discussed above. In fact, miniaturizing ion engine technology presents a formidable challenge. This is in large part because ion engines, unlike FEEP, colloid, or PPT thrusters, require a gaseous discharge to be maintained from which ions can be drawn to generate thrust. Maintaining discharges in smaller discharge volumes, however, leads to higher electron wall losses due to the higher surface-to-volume ratios, and thus may result in less efficient engine designs. In addition, ion engines are complex devices, consisting of a multitude of components that each need to be miniaturized. These include grids (requiring high voltage standoff capability), engine cathodes and neutralizers (which have to operate in hostile plasma environments), as well as micro-feed system components able to handle the high-pressure gaseous xenon flow reliably. Power conditioning units (PCUs) will also need to be miniaturized. PCU miniaturization, however, is a common problem for all electric propulsion devices and not unique to ion engines.

At present, a development program is underway at the Jet Propulsion Laboratory (JPL) to study the feasibility of micro-ion engine approaches and any potential limits of their miniaturization. In the following sections of this article, the JPL micro-ion engine program will be introduced, and the design and fabrication of test hardware will be described. The present activity was newly initiated in 2000, although it is based on earlier development efforts, which were mainly focused on ion engine micro-grids and field emitter array development. These earlier activities provided significant guidance in the design of the current micro-ion engine program and results obtained from these studies, as well as their impacts on the current program will be reviewed in Sect. III.

II. MICRO-ION ENGINE APPROACH

A micro-ion engine currently being developed at JPL is shown in Fig. 1. The concept is based on a MEMS (Microelectromechanical Systems)-hybrid approach, involving both conventionally machined as well as MEMS-fabricated components. Some parts, such as the discharge chamber, are machined using traditional machining

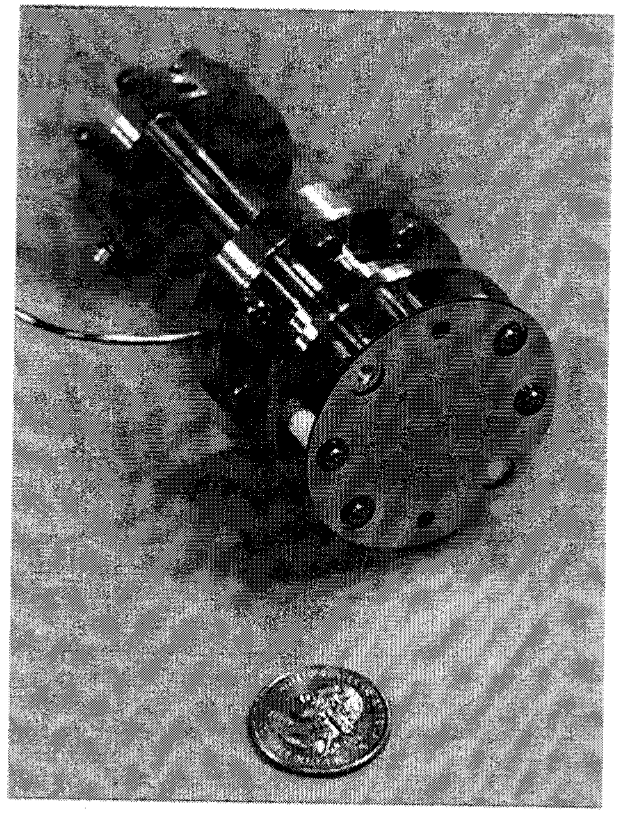

Fig. 1: Micro-Ion Engine Assembly

techniques, while others, such as the cathode and neutralizer, use MEMS technologies in their fabrication. An exploded view of the laboratory model engine is shown in Fig. 2, showing various components, such as (from right to left) grids, grid spacers, grid mount ring, discharge chamber, and a hot-filament cathode assembly (filament and gate electrode) to simulate field emitter arrays in this engine prototype. Design approaches of key components, such as grids and cathodes, are briefly described next, followed by an outlook on other system components, such as power processing units and feed system components which, although not part of this program, will also have to be taken into account when designing a micro-ion engine.

A novel fabrication technology called ChEMS™ (Chemically Etched Miniature Systems) developed by Vacco Industries[12] (to be described below) will be used to fabricate the ion engine grids. Using this technology, more conventional grid design approaches could be chosen, eliminating many of the problems associated with MEMS-based grid designs, which were studied previously[13].

Different engine sizes, varying in diameter between 1 and 3 cm will be studied. These engine sizes are significantly larger than those of the so called "Ion Thruster-on-a-Chip" concept investigated earlier at JPL. As will be discussed below, this change in approach is due to results

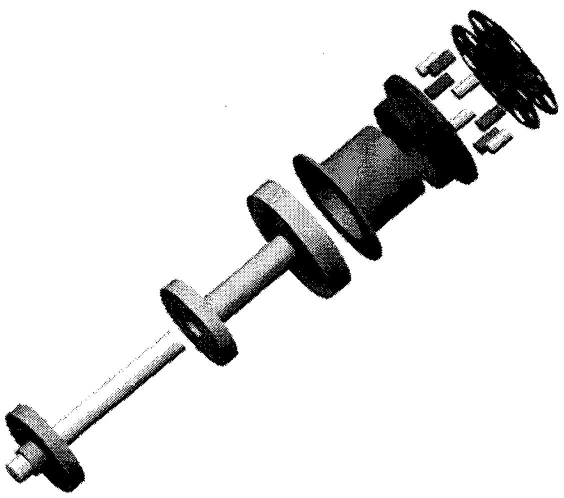

Fig. 2: Exploded View of the JPL Micro-Ion Engine

Fig. 3: A single element of a Mo FEA cathode fabricated at SRI International.

obtained from numerical studies performed at the Massachusetts Institute of Technology (MIT) under contract to JPL, which revealed that such entirely MEMS-based micro-ion engine devices are likely not feasible[14,15].

Engine cathodes and neutralizers may represent one of the most challenging development issues of ion engine miniaturization. Hollow cathodes, typically used for these applications in macroscopic engines, do not lend themselves well for use in micro-ion engines. This is in part due to the complexity of the hollow-cathode design, which complicates miniaturization. Even more importantly, the relatively high power consumption of hollow cathodes is prohibitive for micro-ion engine designs. Micro-ion engines may operate in the 50-W total power range and therefore cannot afford this technology.

At present, field emission (FE) cathode (or cold cathode) technology is considered as one of the most promising options for both micro-ion engine cathodes and neutralizers[16,17]. Different FE design approaches exist, to be elaborated upon below. One typical configuration, with the best performance to-date, is the microfabricated field emission array (FEA) cathode. A section of a FE array is shown in Fig. 3. It consists of micro-machined tips protruding through concentric gate electrode apertures with diameters commonly less than 1 μm.[18] By applying a negative voltage to the tip and a positive voltage to the gate electrode, high electric field strengths can be generated at the tip and electrons tunnel through the potential barrier at the vacuum interface. This process does not require applied thermal energy. Less than 0.1 % of the current is typically collected by the gate electrode. Packing densities of these tips have exceeded 10^8 tips/cm^2. FEA cathodes have demonstrated 100 mA with less than 1 mW consumed by the gate electrode. The result is a low-power consuming electron source that may be used as both engine cathode and neutralizer.

The FE cathode current depends exponentially on the work function and electric field at the tip, with the sharp tip structure providing enhancement of the applied field. The gate voltage required for the desired current will depend on tip radius[19] and gate aperture radius and tip material. In general, however, these voltages can be kept low with the small dimensions achievable by the microfabrication process, maintaining sufficient electric field strengths with only a few tens of Volts. The tip material is typically molybdenum or silicon because the fabrication process with these materials is well developed; however, thin film coatings on these base materials have been applied to reduce the work function of the cathodes and improve their stability in contaminating environments.[20,21,22,23,24]

Challenges facing FEA cathode design are lifetime and space charge current limitations in the thruster plasma environment. The cathode will be required to operate in 10^{-4} – 10^{-3} Torr range for cathode applications, and about 10^{-5} Torr of xenon for neutralizer applications. Although considerable design heritage exists for FEA technology, previous applications have mostly focused on flat panel displays where cathodes operate at plasma pressures usually not higher than 10^{-7} Torr. Operation at higher plasma pressures presents the risk of cathode tip erosion from ion bombardment. Required operating voltages will increase as the tip is sputtered by ion bombardment, ultimately leading to the destruction of the cathode, thus limiting its lifetime. As will be discussed below, several approaches are currently being studied at JPL to cope with these potential problems, including the use of more sputter-resistant and lower work function cathode tip materials and electrostatic ion repeller screens integrated with the field emitter arrays.

Given the challenges involving FEA fabrication, the micro-ion engine will initially be operated with a tungsten hot-filament cathode serving as a "place holder" for later FEA cathodes. The hot-filament cathode is obviously not suited for actual micro-ion engine designs due to its typically high power consumption and very short cathode lifetime that can be achieved in the plasma environment of an ion engine. However, using this cathode will allow the study of chamber and grid designs to progress prior to the availability of a suitable field emitter array cathode and thus accelerate the research program.

In parallel to the experimental investigation of micro-ion engine designs, a detailed numerical study is also being performed, providing a theoretical basis for future design optimizations. The goal is to determine possible limits with respect to miniaturization, and study effects of plasma pressures, grid open-area fractions, magnetic field configurations, or various neutral flow inlet schemes on the engine design in order to maximize engine efficiencies. Using this numerical approach various design combinations can be studied prior to costly fabrication and testing.

This numerical study will be conducted in collaboration with the Air Force Research Laboratory (AFRL) at Edwards AFB. In the current numerical modeling approach, neutral flow field data computed using Direct Simulation Monte Carlo (DSMC) methods provided by AFRL will be used as inputs to a Particle-in-Cell (PIC) code run at JPL to calculate the charged particle flow.

Finally, miniature power conditioning units (PCUs), to be integrated directly with the ion engine body, may be investigated in future years, pending required funding. Typically, PCU masses may contribute significantly to masses of electric propulsion systems. These mass penalties are expected to be even higher in relation to thruster masses as systems are being miniaturized. Novel, micro-electronic "on-the-chip" approaches will be studied. Challenges to be overcome in these designs, besides miniaturization, are the relatively high voltage requirements ranging into the kilo-Volt range for ion engines, coupled with power requirements into the several 10s of Watts, as well as high required PCU efficiencies. At present, a 2-cm^3 module weighing 4.25 grams and providing voltages in the range between 0-$\pm$ 5000 V is available[25]. Unfortunately, output power is limited to a maximum of 1.25 W at present. Future micro-ion engine PCU may be based on higher-power versions of these or similar devices. If they can be made available, a micro-ion engine system could be envisioned where such devices would be directly joined to the ion engine body, forming an ultra-small and compact ion engine system module.

As mentioned previously, ion engines operating on inert gases such as xenon will also require propellant feed system components, such as valves, flow controllers, or regulators. At present, the micro-propulsion program introduced here cannot accommodate the significant development efforts required in this area. However, development efforts with respect to micro-valves[26] and flow controllers are underway elsewhere, and it is anticipated that this program will leverage these activities in the future.

III. PREVIOUS RESEARCH

The micro ion engine concept described in this paper evolved from a more highly miniaturized concept, termed the "Ion Thruster-on-a-Chip" proposed in 1996. In this previous, entirely chip-based concept, micro-machined silicon discharge chambers were envisioned, featuring integrated, batch-fabricated grid structures, FEA cathodes and neutralizers. Segmented accelerator grid structures were proposed to enable electrostatic beam steering, eliminating the need for gimbal structures, which likely would place a heavy mass penalty on any micro-ion engine concept.

Several key feasibility issues could readily be identified for such a microfabricated ion engine approach and were subsequently addressed. These included (1) discharge chamber design, and the ability to maintain gaseous discharges in such small (100 micron wide and several centimeter long) chambers; (2) micro-ion engine grid development and the ability to stand off voltages in the kV-range; as well as, (3) the aforementioned FEA development, and the ability to operate FEAs in hostile, high pressure ($10^{-3} - 10^{-4}$ Torr) plasma environments.

Discharge Chambers

The Massachusetts Institute of Technology was contracted to numerically study the feasibility of microfabricated discharge chambers[14]. Results revealed that maintaining plasmas in microfabricated discharge chambers is extraordinarily difficult and would lead to highly inefficient discharges. In particular the very narrow width of the chambers (100-micron) posed problems. It therefore became quickly apparent that miniaturization goals had to be de-scoped to larger, "meso-scale" engine sizes. As a consequence, 1-3 cm sizes are currently being targeted.

On the high side, the engine size range to be studied was bounded by diameters of available small ion source designs that can be found in the literature[4,27]. Hughes developed a very small xenon ion source for a US Air Force/NASA Goddard spacecraft charging experiment in 1979[20], for example. This ion source was 3.6 cm in diameter, required 45 W of power to produce a thrust of 0.14 mN at a specific impulse of 350 sec[27]. Calculating thrust power from these data to 0.24 W, thruster efficiency can be determined as 0.5%, not accounting for any neutralizer losses. While these performances are low, note, however, that this thruster had not been optimized to function as a propulsion device[27]. A small 5-cm diameter xenon ion engine was developed at Keldysh Research Center in Russia[21]. This engine has been claimed to be able to generate 1 mN thrust at 3100 sec specific impulse at a power level of 50 W[28]. Calculating the beam power from the thrust and specific impulse values one arrives at 15 W, resulting in an engine efficiency of approximately 30%.

These literature data warrant confirmation and further study of meso-scale ion engine concepts. Selecting engine sizes in the 1-3 cm diameter range in the current program therefore represents a significant relaxation from the likely infeasible "Ion-Thruster-on-a-Chip" concept, while still maintaining a very aggressive entry point for engine miniaturization efforts based on previous research.

Grids

While the "Ion-Thruster-on-a-Chip" concept was abandoned based on the negative results obtained in the MIT study, both micro-grid as well as FEA feasibility studies were carried on since it was argued that both could potentially benefit larger, meso-scale thruster designs as well. MEMS-based grid designs were explored in the past JPL program. Based on standard MEMS fabrication techniques, grid designs were studied where screen and accelerator grids consisted of thin-film deposited metals (such as molybdenum), separated by an insulating layer, such as silicon dioxide. Silicon dioxide is commonly used in microfabrication and is an electric insulator material of choice in this field.

However, such a MEMS fabrication scheme immediately opened several feasibility concerns. For example, the continuous insulating oxide layer between the metal thin films (grids) required to support the films could potentially collect material sputtered off of the grids, which could lead to grid shorting. Thus, integrated shadow shielding would have to be explored. Given MEMS grid designs, shadow shielding would have to be batch-fabricated in place during the grid fabrication process.

Even prior to addressing such fabrication difficulties, more fundamental grid design issues had to be addressed, such as the voltage standoff capability of the insulating silicon dioxide film. Literature data were typically found to be limited to much thinner (sub-micron) oxide films, unable to stand off the assumed grid voltages in excess of 1 kV. Therefore, a series of experiments was conducted aimed at determining the dielectric strength of thick (up to 4 micron) silicon dioxide films.

Data were obtained for electric breakdowns through the substrate of the oxide material located between two thin-film electrodes representing screen and accelerator grids (substrate breakdowns) and along oxide surfaces (surface breakdowns), representing the possible case of breakdowns along exposed oxide surfaces on grid aperture walls[13,15]. During substrate breakdowns, silicon oxide was found to have excellent breakdown characteristics, able to stand off 600-700 V/micron[13]. Silicon oxide can typically be deposited up to a thickness of 5 microns using standard thin-film deposition techniques. Therefore, at maximum obtainable oxide thicknesses, substrate breakdown field strengths in excess of 3 kV appear attainable. Oxide substrate breakdown field strengths were shown to vary only slightly with temperature, not expected to change the mentioned results significantly at elevated grid temperatures.

Unfortunately, surface breakdown field strengths were found to be much lower, around 200 V/micron over a 5 micron gap, dropping below this value for larger gaps. Over a thickness of 5 micron, silicon oxide can therefore only be expected to standoff about 1 kV, being of marginal performance for grid applications[13]. While it is uncertain at this point what ion engine grid requirements will be for future microspacecraft or interferometry missions, assuming similar grid voltage requirements as for macroscopic engines is a good, conservative first approximation. This assumption and the results obtained from the grid breakdown tests therefore warrant the examination of other grid fabrication techniques as well, to be addressed in the course of this study.

Cathodes

FEA cathode technology is also likely to play an important role in meso-scale engine technology as no credible alternative to this technology currently exists. Si, Mo, and C field emitter cathodes have been tested in xenon environments with pressures representative of the thruster environments at 10^{-6}-10^{-5} Torr.[29] Carbon film cathodes operated at low efficiency and high voltages but showed no performance degradation in xenon environment. The I-V curve obtained in $2x10^{-5}$ Torr of xenon was no different from the I-V characteristic in UHV. On the other hand, the performance of Mo and Si FEA cathodes was very sensitive to the operating environment. The Mo and Si cathodes were permanently damaged by ion bombardment with operating voltages >58 and 60 V, respectively. From experimental and theoretical results it was concluded that the energy threshold for sputtering Mo and Si with Xe ions is 39 eV and 45 eV, respectively.

In order to prevent the formation of self-generated doubly charged xenon ions, which dominate the erosion process in the space between the tips and gate electrode, operating voltages are limited to ≤37 V. This operating voltage limitation is independent of cathode material. The charge exchange ion population is accelerated between the plasma and gate electrode, which is typically ~20 V. This population also consists of both double and single ions. They further limit the operating voltages to 5 (Mo) and 12 V (Si).

Further development of these FEA cathodes is necessary to achieve the performance and lifetime required by an ion thruster. An electrostatic ion shield has been proposed to deflect CEX ions from the microtips and decouple the electron energy from the gate electrode potential. This Cathode Lens and Ion Repeller (CLAIR) is currently under development. It will enable the cathodes to operate at 35 V and meet the lifetime requirements. Current limiting architectures may also be integrated into next generation cathodes to prevent premature arcing events and obtain lifetime objectives which are in excess of 6000 hours. Thin film coatings on Mo and Si FEAs, like ZrC, HfC, and

C, are recommended to lower the cathode work function and increase the energy threshold for sputtering.

Space charge limited electron emission has also been modeled with a simple one-dimensional analytical and numerical model and a three-dimensional PIC code.[30] The one-dimensional model has been used to study the effect of energy on the current density limits for a planar and spherical sheath configuration. These results provide upper and lower current density limits, which bound the results of the three-dimensional model. The three-dimensional model predicted a current density limit between 125 and 236 mA/cm^2 in a plasma characterized by an ion and electron number density (neo) of 8x10^8/cm^2, electron temperature (Te) of 5 eV, and electron energy (V_g) of 30 eV. In that case the cathode area was 0.22 cm^2.

Figure 4 shows the expected performance from an optimistic cathode configuration, the current density limited by the plasma environment, and operating voltage limited by cathode structure and lifetime. The predicted Fowler-Nordheim FEA cathode current density, J_{FN}, is shown for Mo (ϕ_w=4.35 eV), Si, (ϕ_w=4.0 eV) and HfC or ZrC (ϕ_w=3.5 eV) FEAs, with the material work function being represented by ϕ_w. The cathode configuration considered has an effective tip radius of 40 Å, 5x10^7 tips/cm^2, and gate aperture radius of 2000 Å. The limits on the current densities, J_{s-c}, for three plasma regimes are shown as a function of energy. The current density limits for regime one are bound by the planar and spherical one-dimensional sheath model results. A cathode area of 1.5 cm^2 was assumed in the spherical sheath model. The current density limits shown for case 2 and 3 were obtained by the planar sheath model, therefore representing a lower bound on the limit. These predicted limits exceed the current emission capabilities of FEA cathodes, so the performance in these environments will not be limited by space charge effects. The operating voltage thresholds, J_{th}, both with and without the CEX ions are shown in the figure. The current density objective, J_{goal}, of 100 mA/cm^2 is also shown in the graph. Data in this graph show that materials like HfC or ZrC with work functions of 3.5 eV or lower are required to provide at least 100 mA/cm^2 at gate electrode voltages ≤35 V.

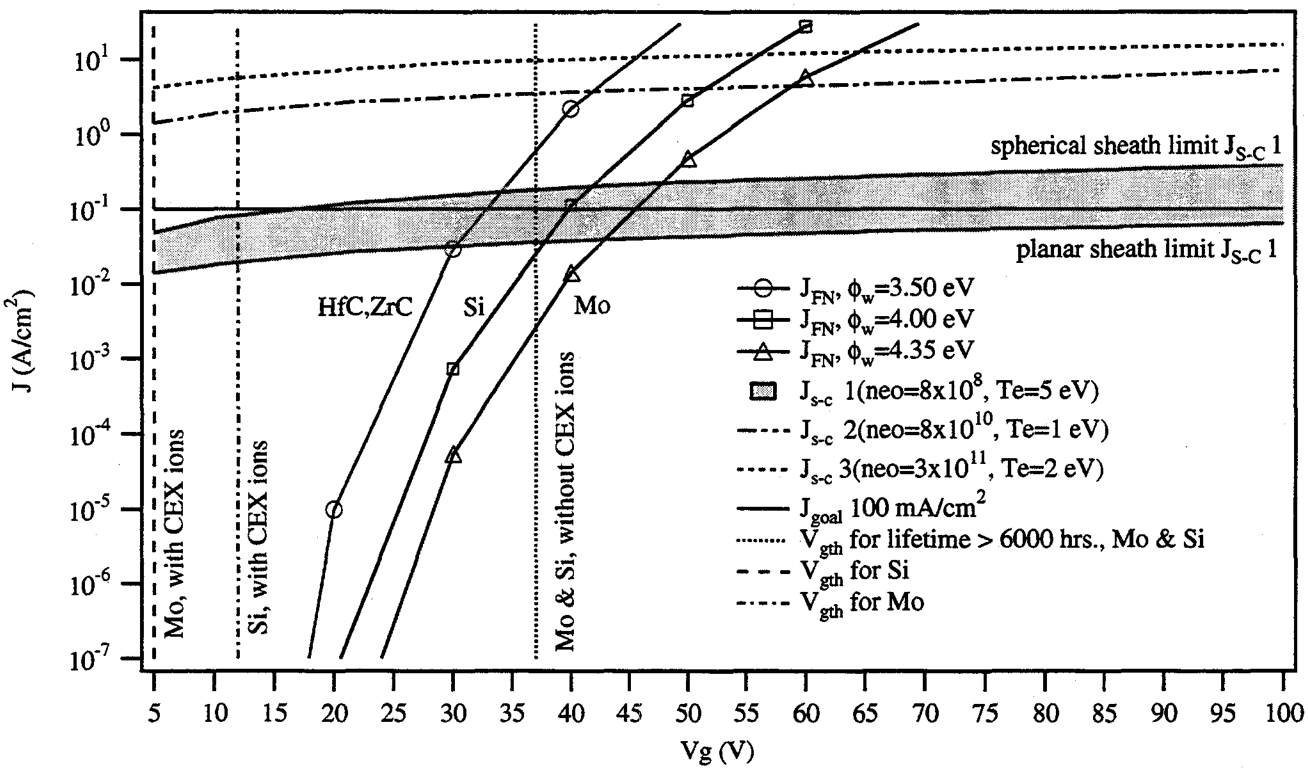

Fig. 4: Performance requirements and limitations of field emission cathodes operating in xenon thruster environments.

IV. DESIGN AND FABRCIATION OF MICRO-ION ENGINE TEST HARDWARE

Discharge Chamber

Three discharge chamber configurations will be tested. The diameters of the chambers are 1, 2, and 3 cm and the length of each is the same as the diameter. The 3-cm engine design was shown in Fig. 1. Various engine diameters were selected to account for the uncertainty that exists at present regarding the degree of miniaturization that may be achievable for an ion engine. Evaluating performances of these designs in addition to numerical calculations performed in context with these experiments will allow minimum practical engine diameters to be determined.

All three engine bodies may be outfitted with the same grid system, to be described below, thus reducing the cost of the assemblies. Oversized flanges on the smaller discharge chambers will mask portions of the grid to make them suitable for installation on the smaller engine sizes as well. Solenoids will be placed over the discharge chamber to generate a divergent magnetic field. Use of electromagnets is not an option for space applications due to the power limitation on spacecraft and microspacecraft in particular. However, in the experimental investigation of this engine it will provide flexibility and allow different magnetic field designs to be studied quickly and efficiently. The engine also was fabricated with a highly flexible geometry, which can support different magnetic field configurations and chamber lengths for performance optimization. At present, this engine design is outfitted with a gated hot-filament cathode designed to inject electrons at energies which simulate the characteristics of field emitter array cathodes, which will be integrated with the engine design at a later stage. This filament cathode will obviously not provide the lifetimes desired for an ion engine, however, will allow for the test and evaluation of various engine configurations in parallel to field emitter cathode development.

Grids

The grids were machined from 150 micron (existing stock) molybdenum sheets by Vacco Industries using proprietary ChEMS™ technology[12]. This fabrication technology relies on precision etching of either metals or plastics. Machining tolerances are typically better than those obtained with more traditional machining techniques (i.e. Electric Discharge Machining, laser machining, etc., typically yielding 50 micron (0.002") tolerances) but less than are obtainable with state-of-the-art silicon-based MEMS technologies, achieving tolerances of 1 micron or less in special cases.

ChEMS™ offers similar benefits to MEMS technology, such as cost-effective batch fabrication[12]. Bonding a multitude of previously ChEMS™ etched layers of material one can assemble three dimensional structures[12]. ChEMS™ offers a significant advantage over MEMS by being able to use metals and plastics as base materials, rather than silicon[12]. Although silicon is a stronger material, metals are less brittle. In special cases, such as the grid designs considered here, metals such as molybdenum offer superior sputter resistance. Although MEMS technologies are available to deposit molybdenum in thin films, the thinness of these films makes them highly sensitive to arcing, possibly causing the melting and/or vaporization of large portions of a grid material (see Ref. 13). MEMS thin films will also require a continuous layer of insulator material between the grids to mechanically support these films. This insulating layer may be susceptible to shorting due to sputter deposition of conducting films at locations where it is exposed to the plasma environment, such along grid aperture walls.

The ChEMS™-machined molybdenum grid system used in this study consists of a standard two-grid optics featuring screen and accelerator grid (see Fig. 5). Active beam diameter for the grid is 3 cm, and overall grid diameter is 5 cm to allow for the placement of mounting holes. Note that in the initial experiments the grids will be mounted via screws and boron nitride spacers to a grid mount ring. Mounting screws add considerably to the size and weight of the grid system. In the future, more sophisticated designs will seek to eliminate them. As mentioned above, one grid system design will be used for all discharge chambers (1-, 2-, and 3-cm diameter). In the case of the smaller chambers, sufficiently oversized flanges will allow for grid mounting, and the mounting flange will mask off grid areas exceeding chamber diameters. Grid gap will be approximately 100 micron.

Grid apertures in the screen grid are 330 micron and in the accelerator grid are 200 micron, resulting in open-area-fractions of 45.6% and 16.8% for the screen and accelerator grids, respectively. Higher screen grid open area fractions with an aperture diameter of 400 micron had been targeted. However, the etching process results in concave shapes for the aperture walls as can be seen in Fig. 6. This

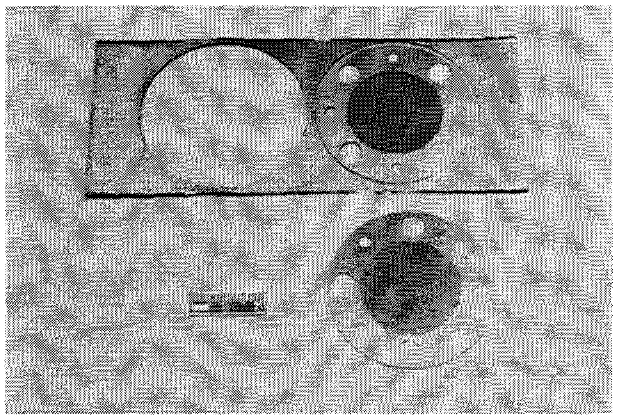

Fig. 5: ChEMS™-Machined Molybdenum Ion Engine Grids (Vacco Industries)

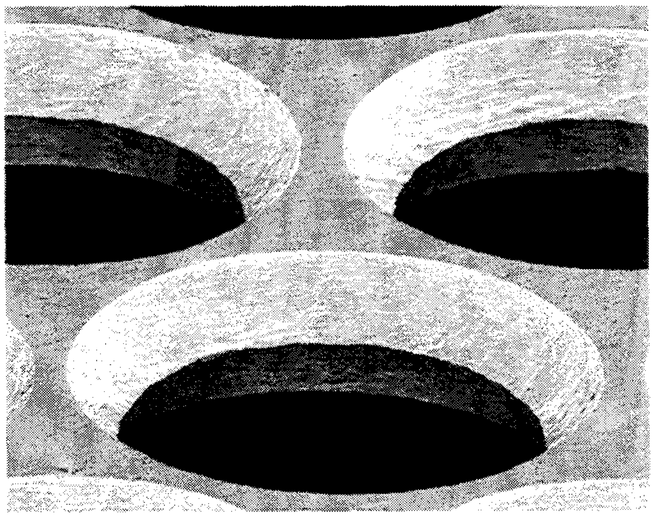

Fig. 6: Close-Up of tGrid Apertures of the ChEMS™ Machined Screen Grid

shape is typical for chemical etching processes and has been observed before for thicker, conventional grids. Typically, the wall material protruding into the aperture is sputter-eroded during grid operation and the aperture eventually opens to its nominal diameter. Future grid designs may rely on even thinner grids, which may reduce underetching of the aperture diameter.

Note that tests and numerical simulations may dictate the use of grids featuring smaller open-area-fractions. In order to achieve shorter electron mean free paths in smaller discharge chambers, discharge pressure may have to be increased, which could possibly be achieved by using smaller open-area-fraction grids. Such grids would limit the beam currents and thrust values that can be obtained with such an engine, however, will potentially result in higher engine efficiencies and thus result in an overall improved system design.

Cathodes

FE cathodes compatible with the micro-ion engine are under development. Mo FEA cathodes with 50,000 tips and 0.7 μm gate aperture radii are being tested in xenon environments to validate theoretical results which show that operating these cathodes with a gate electrode voltage less than 37 V will prevent irreversible structural damage caused by ion bombardment.[31] Preliminary results showed that the cathodes were not irreversibly damaged while operating at gate voltages of 37, 38, 39, 40, 41, 42, and 43 V. However, a reversible change in performance did occur. The current decreased by one order of magnitude when the pressure was increased from 10^{-9} Torr to $2x10^{-5}$ Torr of xenon. Partial pressures of 10^{-8}-10^{-7} Torr of oxygen and nitrogen could be responsible for surface films and changes in work function which caused this temporary change in performance. Under heavy xenon ion bombardment an oxygen or nitrogen film was not expected to be stable. It is interesting to note that these performance changes occur only when the cathode is operating in the higher pressure environments. Further experiments are being conducted to resolve the unexpected experimental results obtained.

The dimensions and configurations of the cathodes tested have not yet been optimized to provide the required current density and lifetime. Mo cathodes are being fabricated with carbide coatings, and will be tested later this year. It is expected that these cathodes will demonstrate much more stable performance than Mo cathodes in elevated pressure environments. The next phase of this research will produce the Mo and carbide coated FEA cathodes with much smaller gate aperture diameters and larger tip packing densities and arrays of tips. CLAIR configurations are under development, and current limiting architectures which are required to achieve lifetimes of thousands of hours will also be addressed. The next phase of this program will include the integration and testing of CLAIRs and FEA cathodes. The cathodes will be developed to provide more than 100 mA/cm^2 at approximately 35 V.

V. NUMERICAL MODELING

As an ion thruster is scaled down toward a micro-ion thruster, several key issues need to be resolved, such as the limitations on containing electrons, initiating and sustaining a gas discharge in a micro-discharge chamber, and the limitations on ion acceleration. Currently, the physics underlying these issues are not well understood. As a result, the baseline parameters for the design and operation of a micro ion engine and the scaling laws are yet to be identified.

To assist the design of a micro ion engine, a physics-based numerical research effort has been initiated. The objectives of the modeling are first to identify the baseline design parameters and scaling laws, and then to use the simulation model as a numerical test bed for an actual micro ion engine. To achieve these objectives, a particle-in-cell (PIC) and Direct Simulation Monte Carlo (DSMC) based model is being developed as a joint research program between AFRL and JPL. The AFRL effort focuses on the neutral flow and the JPL effort concentrates on discharge and plasma flow.

As part of the JPL effort, a full particle 3-dimensional Particle-In-Cell with Monte Carlo Collision (PIC-MCC) code was developed to model the micro ion engine. In this model, both the electrons and ions are treated as test particles. Their trajectories, space charge, and the electric field are solved self-consistently using the standard PIC algorithm. For those plasma particles that impinge upon neutral particles, a Monte-Carlo collision subroutine is called to determine whether a collision has occurred and to calculate the after-collision velocity. The neutrals are treated separately. This is possible under conditions where ionization fractions are low, and the effect of ionization on the neutral particle count is only small. Simulations of the neutral particles in a micro-ion engine discharge chamber are currently being performed by AFRL. The neutral density is used as an input to the PIC-MCC simulation.

To date, this PICMCC code has been used to simulate a simplified micro-ion engine discharge chamber to study the initiation of a discharge. Calculations were performed for a 2cm x 2cm x 2cm discharge chamber which uses either a field emitter cathode or a regular thermal filament for the electron source. A magnetic field of 5 to 50G is used to confine the electrons. Initial results show that a gas discharge can be readily initiated if the neutral gas pressure is equal to, or larger than, 0.01 Torr. These pressure values are high, and will impact the design of other engine components, such as cathodes and grids (open-area-fractions)

VI. CONCLUSIONS

The micro-ion engine is under development. The grids and discharge chamber have been fabricated and assembled. Molybdenum grids were machined using a novel ChEMS™ micromachining technology developed by Vacco Industries. A filament cathode has been assembled and demonstrated that it can generate and sustain a plasma discharge in the engine discharge chamber. The FEA cathode configuration is being optimized with materials and configuration to provide electrons for propellant ionization and ion beam neutralization and meet the performance and lifetime objectives. This cathode will eventually replace the filament cathode. A three-dimensional PIC model is being used to evaluate the effect of anode, cathode, and screen grid potential and magnetic field configuration on discharge efficiency. Magnetic field configuration must be optimized for each engine configuration. Magnetic field optimization, thruster performance evaluations, and FEA cathode testing will be the focus of the next phase of this research.

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